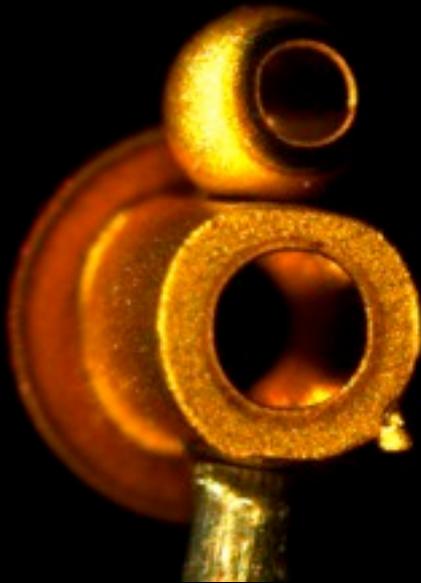


Plasma physics at the Z6 station, GSI

Energy loss of heavy ions in plasma and laser ion acceleration



A. Ortner^{1,2}, V. Bagnoud², M.M. Basko^{3,4}, S. Bedacht², A. Blazevic¹, S. Busold²,
W. Cayzac², O. Deppert², S. Faik³, A. Frank¹, A. Knetsch², D. Kraus², T.
Rienecker², D. Schuhmacher¹, An. Tauschwitz^{2,3}, F. Wagner², G. Schaumann²,
M. Roth²



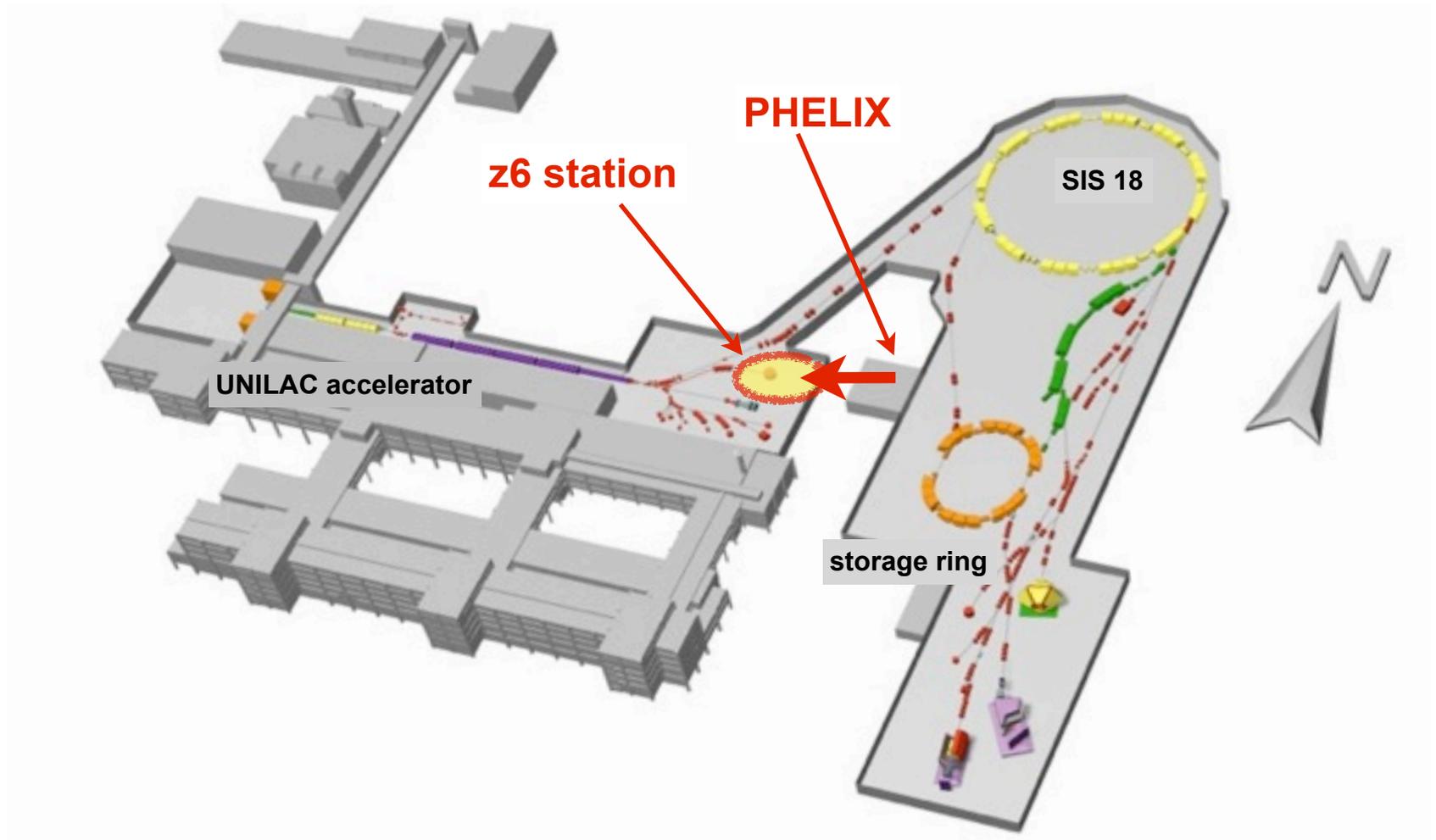
¹ Institut für Kernphysik, Technische Universität Darmstadt, Germany

² GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

³ Universität Frankfurt, Darmstadt, Germany

⁴ ITEP Moscow, Russia





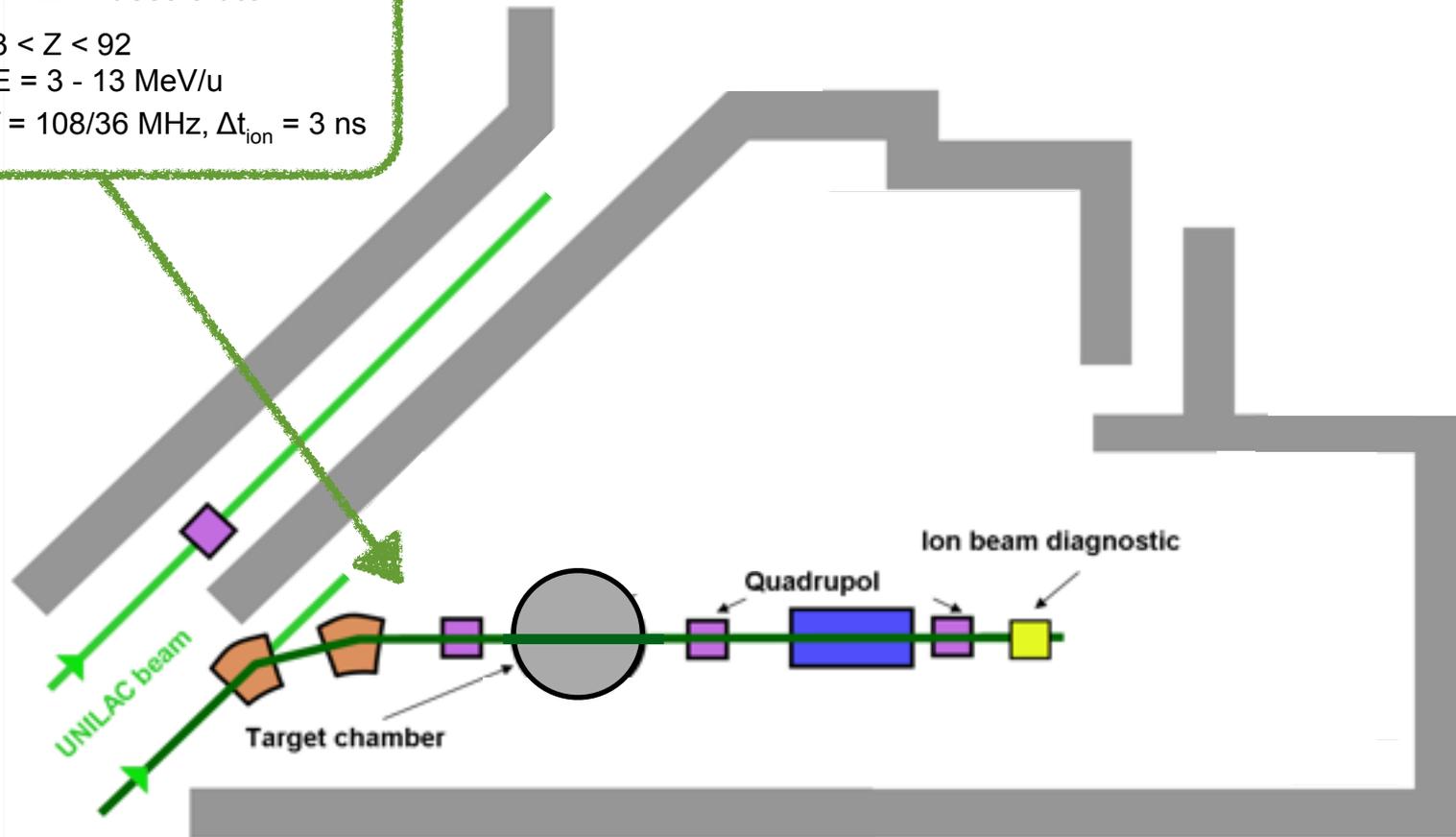
Z6 station - high energy lasers and ion beam -

UNILAC accelerator

$$3 < Z < 92$$

$$E = 3 - 13 \text{ MeV/u}$$

$$f = 108/36 \text{ MHz}, \Delta t_{\text{ion}} = 3 \text{ ns}$$



Z6 station - high energy lasers and ion beam -

UNILAC accelerator

$$3 < Z < 92$$

$$E = 3 - 13 \text{ MeV/u}$$

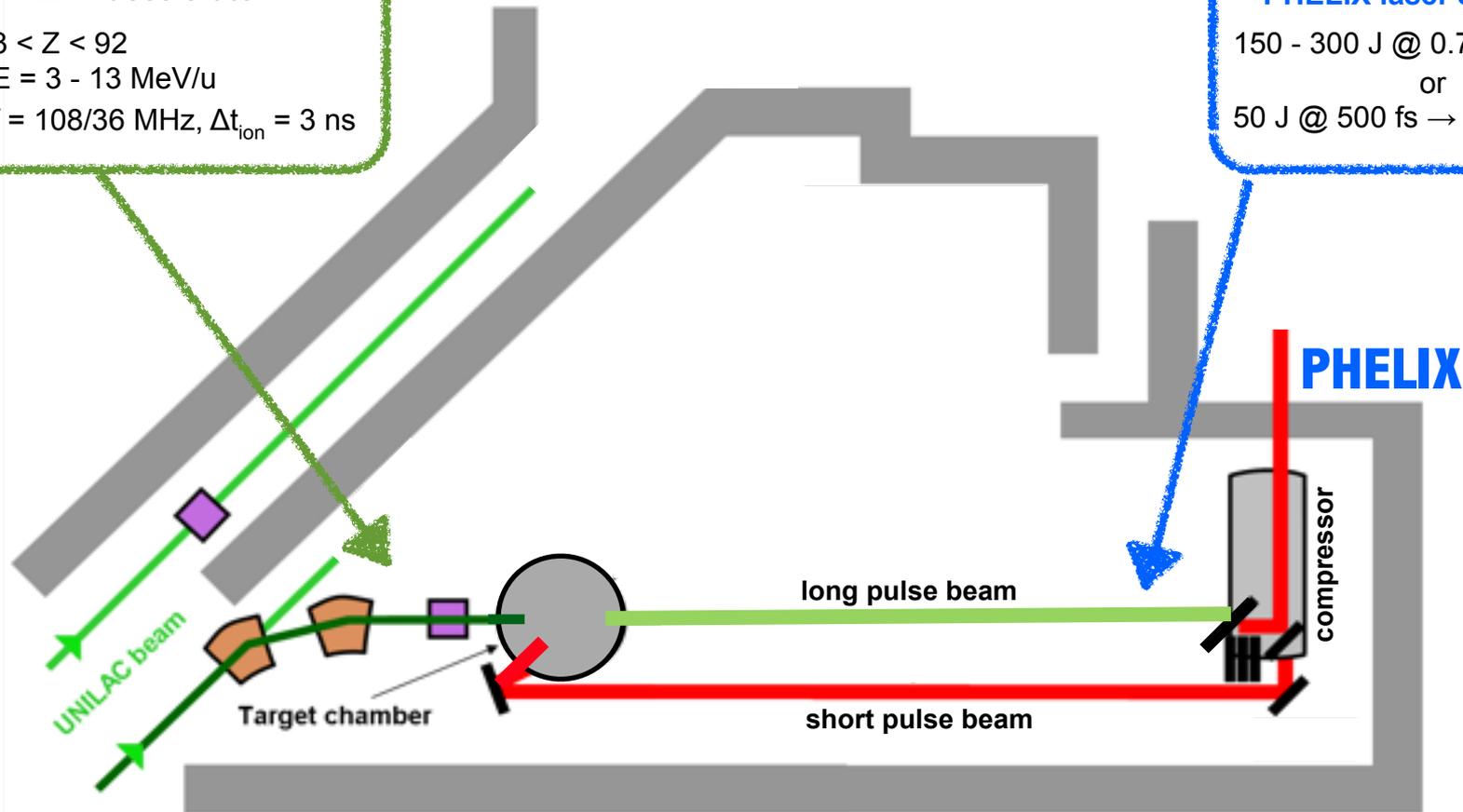
$$f = 108/36 \text{ MHz}, \Delta t_{\text{ion}} = 3 \text{ ns}$$

PHELIX laser system

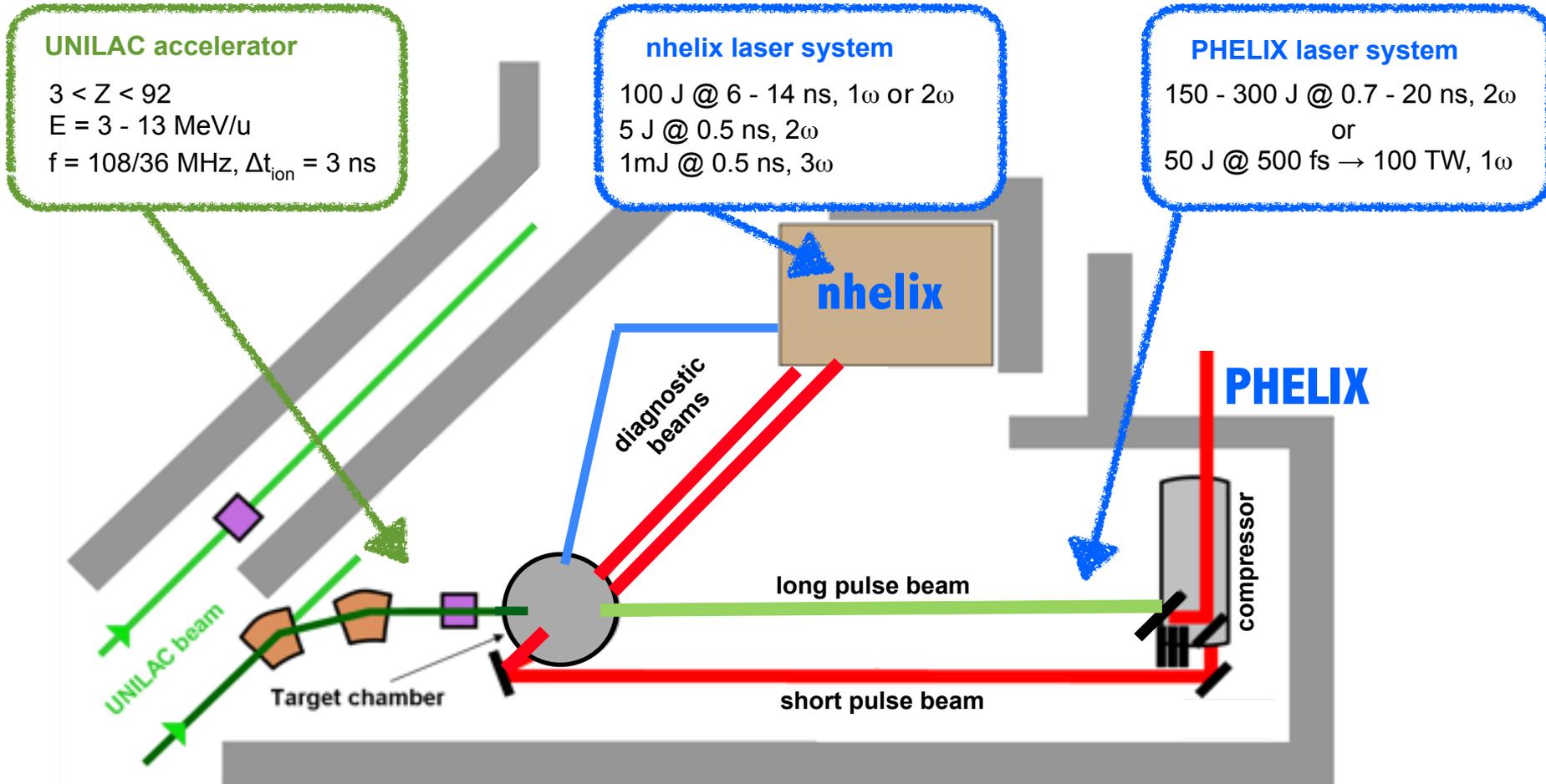
$$150 - 300 \text{ J @ } 0.7 - 20 \text{ ns}, 2\omega$$

or

$$50 \text{ J @ } 500 \text{ fs} \rightarrow 100 \text{ TW}, 1\omega$$



Z6 station - high energy lasers and ion beam -



Z6 station - high energy lasers and ion beam -

UNILAC accelerator

$3 < Z < 92$
 $E = 3 - 13 \text{ MeV/u}$
 $f = 108/36 \text{ MHz}, \Delta t_{\text{ion}} = 3 \text{ ns}$

nhelix laser system

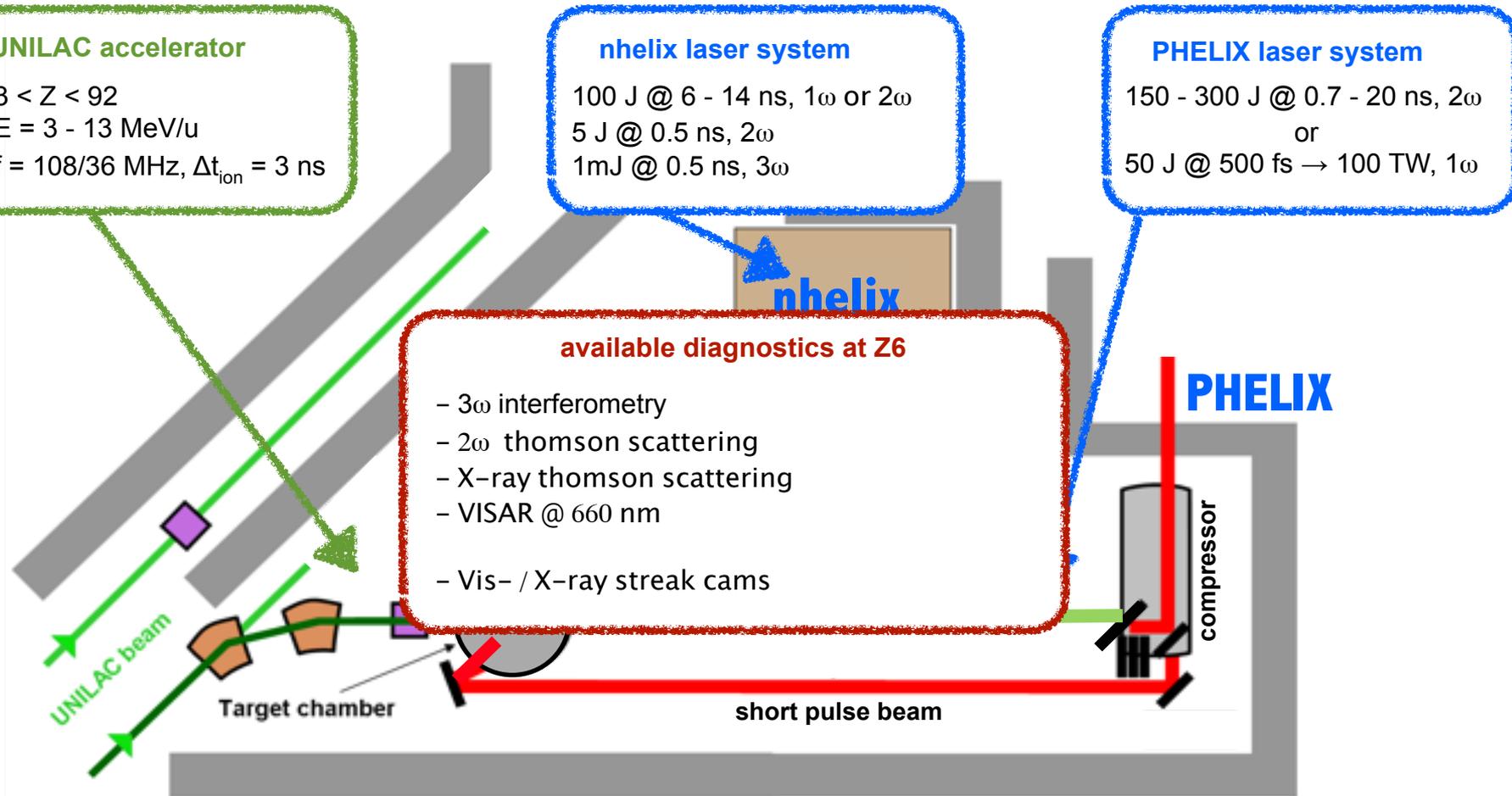
100 J @ 6 - 14 ns, 1ω or 2ω
5 J @ 0.5 ns, 2ω
1mJ @ 0.5 ns, 3ω

PHELIX laser system

150 - 300 J @ 0.7 - 20 ns, 2ω
or
50 J @ 500 fs \rightarrow 100 TW, 1ω

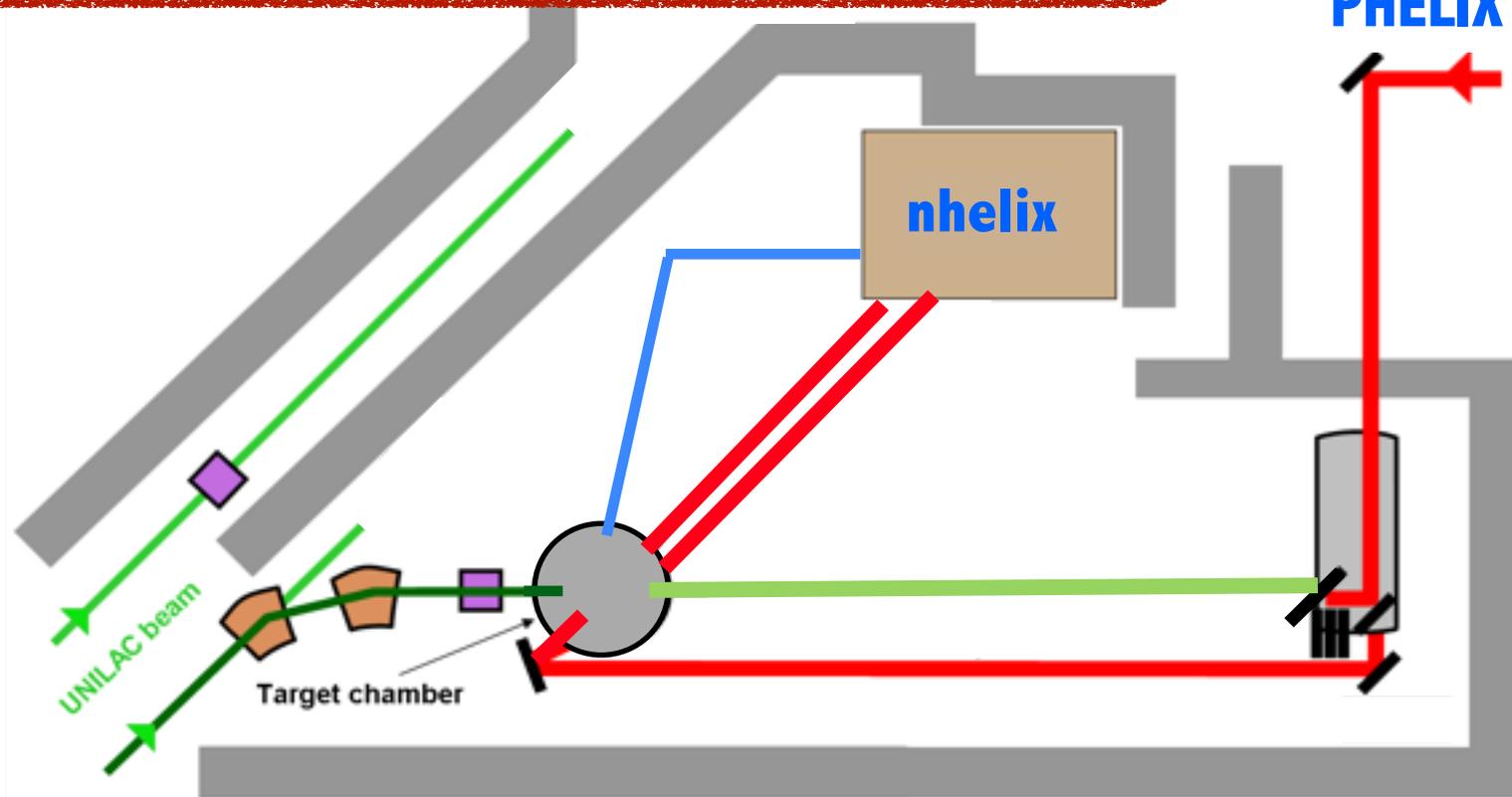
available diagnostics at Z6

- 3ω interferometry
- 2ω thomson scattering
- X-ray thomson scattering
- VISAR @ 660 nm
- Vis- / X-ray streak cams



Z6 station - scientific program -

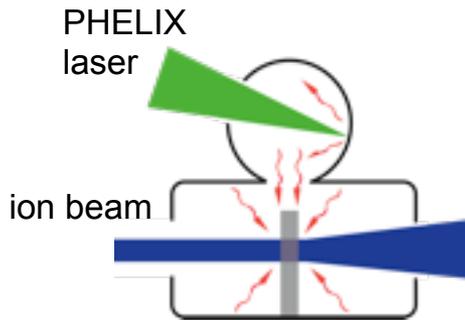
towards the nonlinear regime of ion stopping in plasma
beam-plasma correlations, nonideal plasma



Z6 station - scientific program -

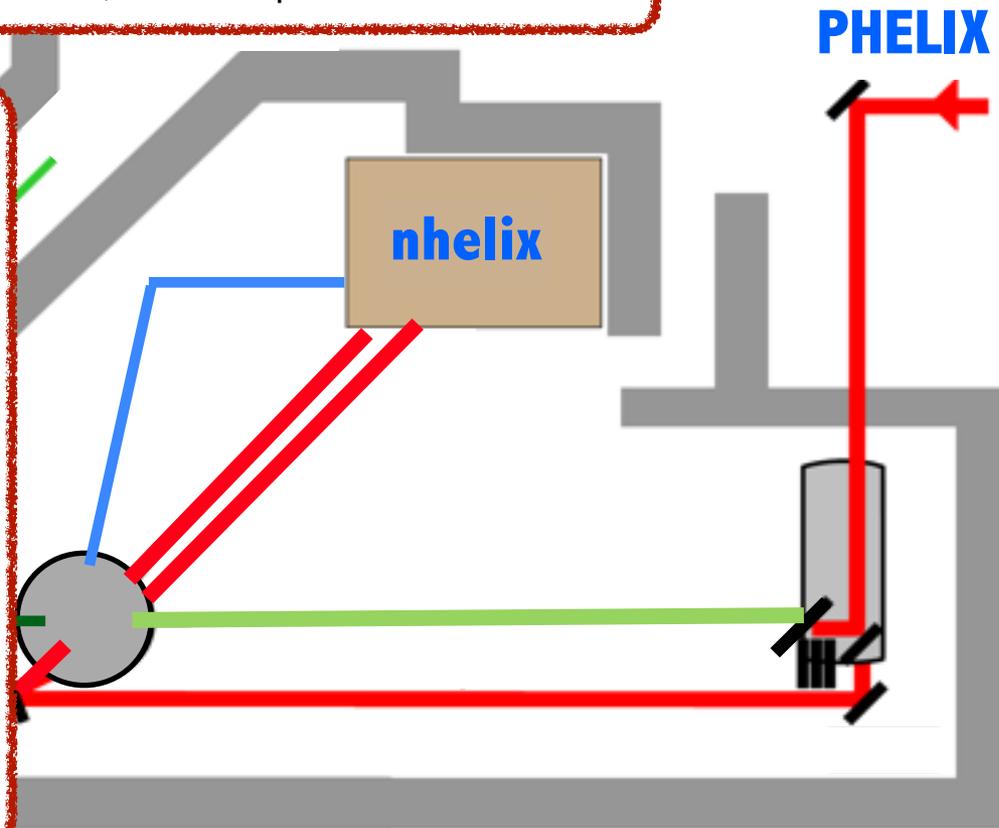
towards the nonlinear regime of ion stopping in plasma
beam-plasma correlations, nonideal plasma

indirect heating with x-ray
probed by swift ions



plasma parameters:

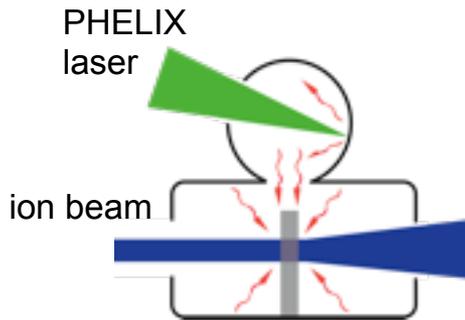
- $\Gamma \sim 0.5-1$ (coupled)
- moderate $T_e \approx 15-30$ eV
- high density $\rho_e \approx 10^{22}$ cm⁻³
- moderately ionized



Z6 station - scientific program -

towards the nonlinear regime of ion stopping in plasma
beam-plasma correlations, nonideal plasma

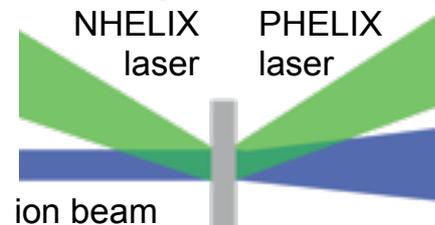
indirect heating with x-ray
probed by swift ions



plasma parameters:

- $\Gamma \sim 0.5-1$ (coupled)
- moderate $T_e \approx 15-30$ eV
- high density $\rho_e \approx 10^{22}$ cm⁻³
- moderately ionized

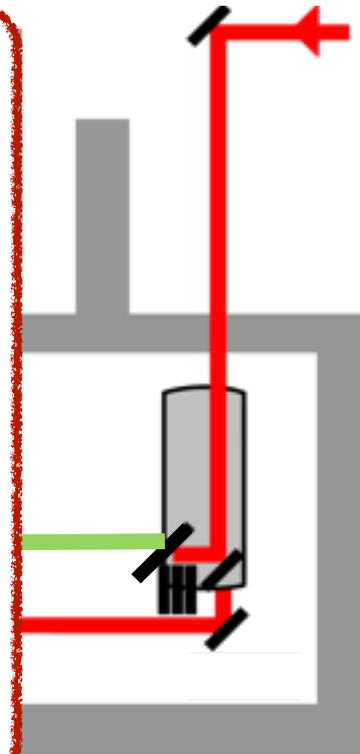
direct laser heating
probed by slow ions



plasma parameters:

- high $T_e \approx 200$ eV
- density $n_e \approx 10^{20}$ cm⁻³
- fully ionized, ideal

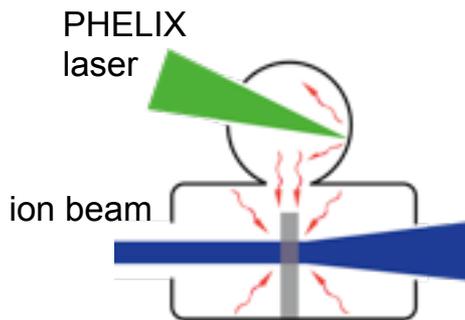
PHELIX



Z6 station - scientific program -

towards the nonlinear regime of ion stopping in plasma
beam-plasma correlations, nonideal plasma

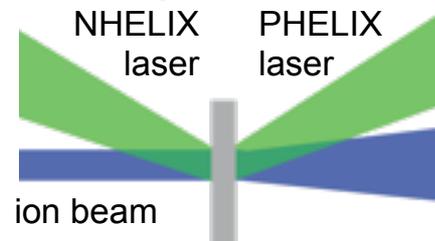
**indirect heating with x-ray
probed by swift ions**



plasma parameters:

- $\Gamma \sim 0.5-1$ (coupled)
- moderate $T_e \approx 15-30$ eV
- high density $\rho_e \approx 10^{22}$ cm⁻³
- moderately ionized

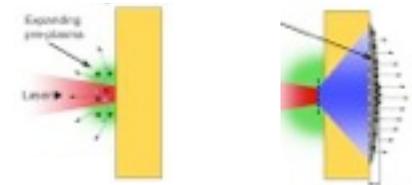
**direct laser heating
probed by slow ions**



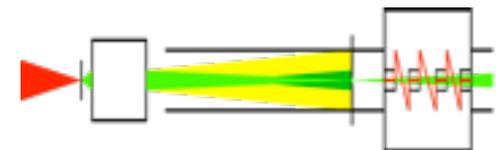
plasma parameters:

- high $T_e \approx 200$ eV
- density $n_e \approx 10^{20}$ cm⁻³
- fully ionized, ideal

the LIGHT project
laser ion generation, handling
and transport



ion generation by TNSA



Injection of laser accelerated
protons into conventional
accelerator structures

parameters:

- 50 J @ 500 fs -> 100 TW
- 10^{10} protons @ 10 MeV

towards the *nonlinear regime* of ion stopping in plasma

no perturbation

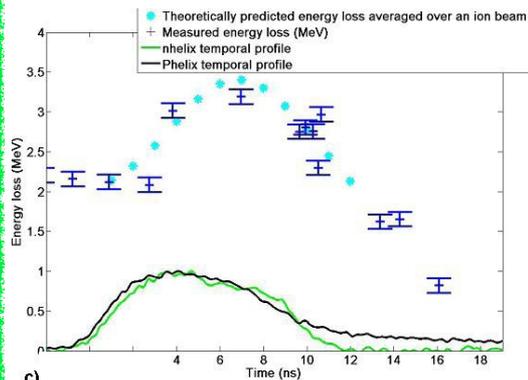
linear regime

semi-linear regime

nonlinear regime

ideal plasma,
swift ions ($v_{\text{ion}} \gg v_{\text{th}}$)

- profound theories
- sufficient experimental data



towards the *nonlinear regime* of ion stopping in plasma

unknown:

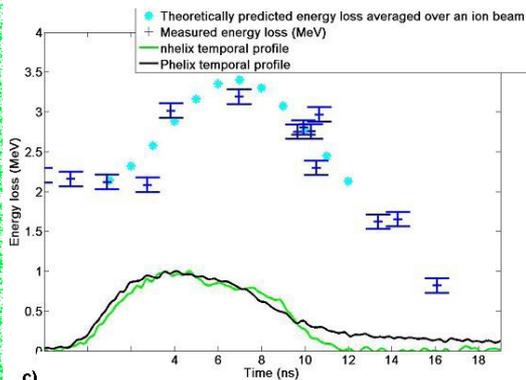
no perturbation

linear regime

ideal plasma,
swift ions ($v_{\text{ion}} \gg v_{\text{th}}$)



- profound theories
- sufficient experimental data



weak perturbation

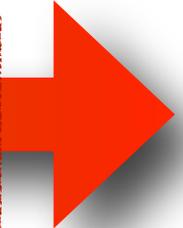
semi-linear regime

ideal plasma
low ion velocity ($v_{\text{ion}} \sim v_{\text{th}}$)
beam-plasma interactions

strong perturbation

nonlinear regime

nonideal plasma ($\Gamma > 0.1$)
coupled plasma
beam-plasma correlations



towards the *nonlinear regime* of ion stopping in plasma

unknown:

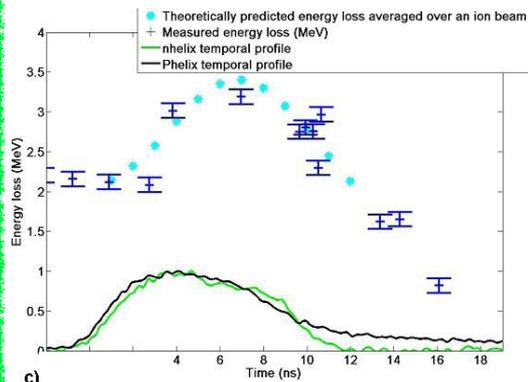
no perturbation

linear regime

ideal plasma,
swift ions ($v_{\text{ion}} \gg v_{\text{th}}$)



- profound theories
- sufficient experimental data



weak perturbation

semi-linear regime

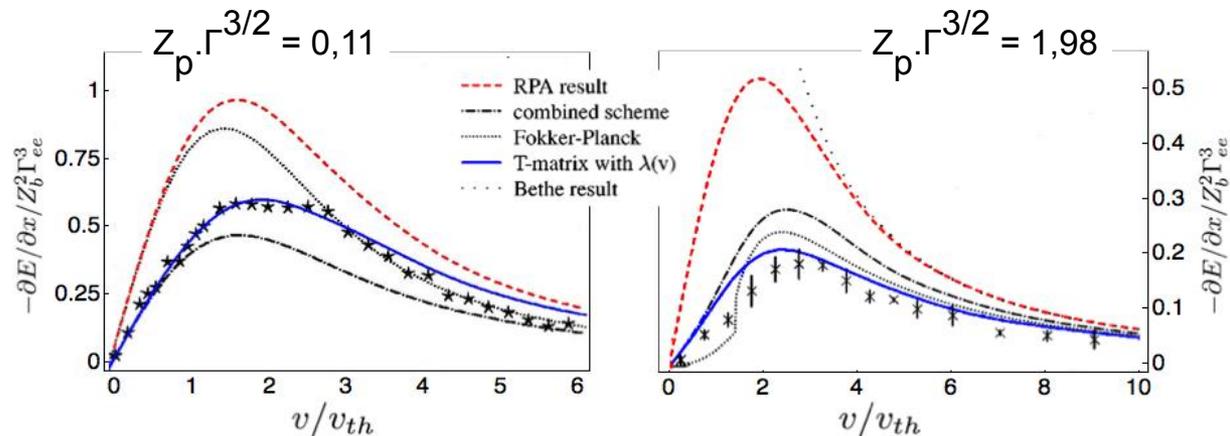
ideal plasma
low ion velocity ($v_{\text{ion}} \sim v_{\text{th}}$)
beam-plasma interactions

strong perturbation

nonlinear regime

nonideal plasma ($\Gamma > 0.1$)
coupled plasma
beam-plasma correlations

strong discrepancies between theories
hardly any experimental data



from D.Gericke et al. (1999 & 2003)

towards the *nonlinear regime* of ion stopping in plasma

unknown:

no perturbation

linear regime

ideal plasma,
swift ions ($v_{\text{ion}} \gg v_{\text{th}}$)

weak perturbation

semi-linear regime

ideal plasma
low ion velocities

strong perturbation

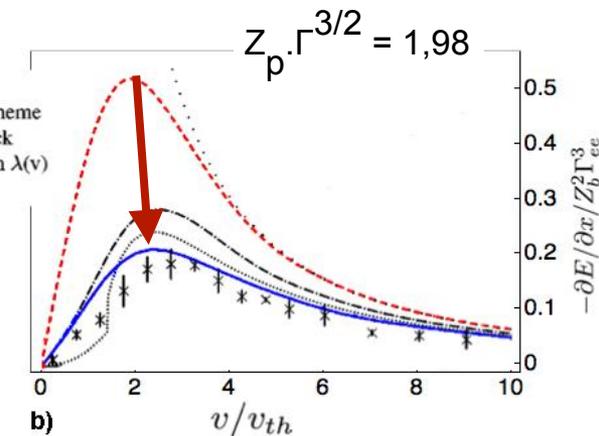
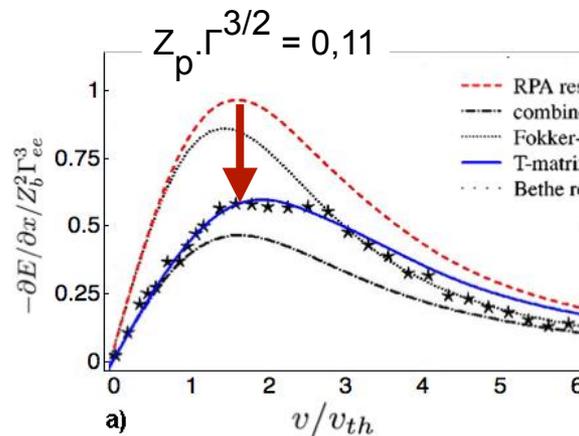
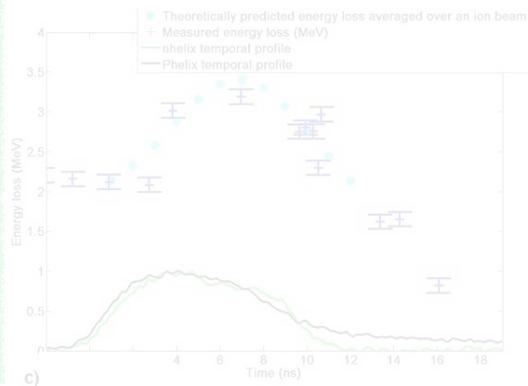
nonlinear regime

nonideal plasma ($\Gamma > 0.1$)
hot plasma
plasma correlations

expected:

reduction of stopping power of 30-50%

solide theorien
viele Daten
gut vermessen



from D.Gericke et al. (1999 & 2003)

towards the *nonlinear regime* of ion stopping in plasma

unknown:

no perturbation

linear regime

ideal plasma,
swift ions ($v_{ion} \gg v_{th}$)

weak perturbation

semi-linear regime

ideal plasma
low ion velocity ($v_{ion} \sim v_{th}$)
beam-plasma interactions

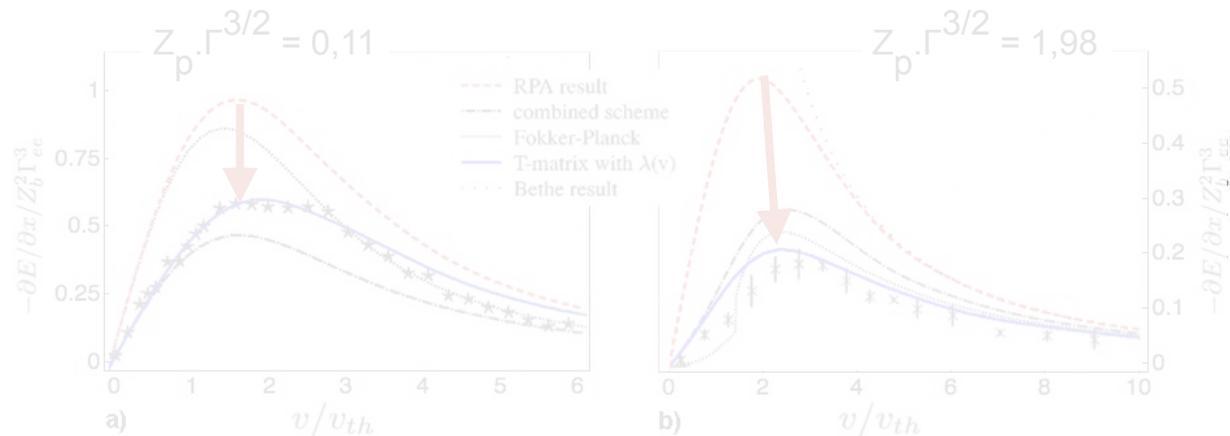
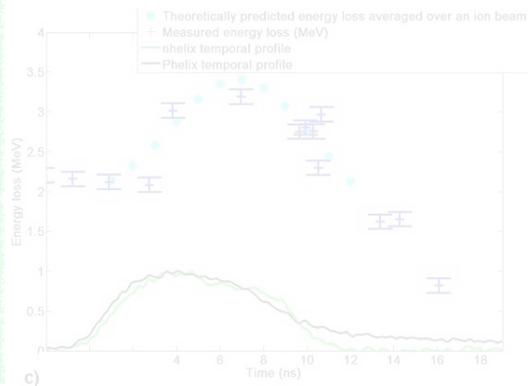
strong perturbation

nonlinear regime

nonideal plasma ($\Gamma > 0.1$)
coupled plasma
beam-plasma correlations

strong discrepancies between theories
hardly any experimental data

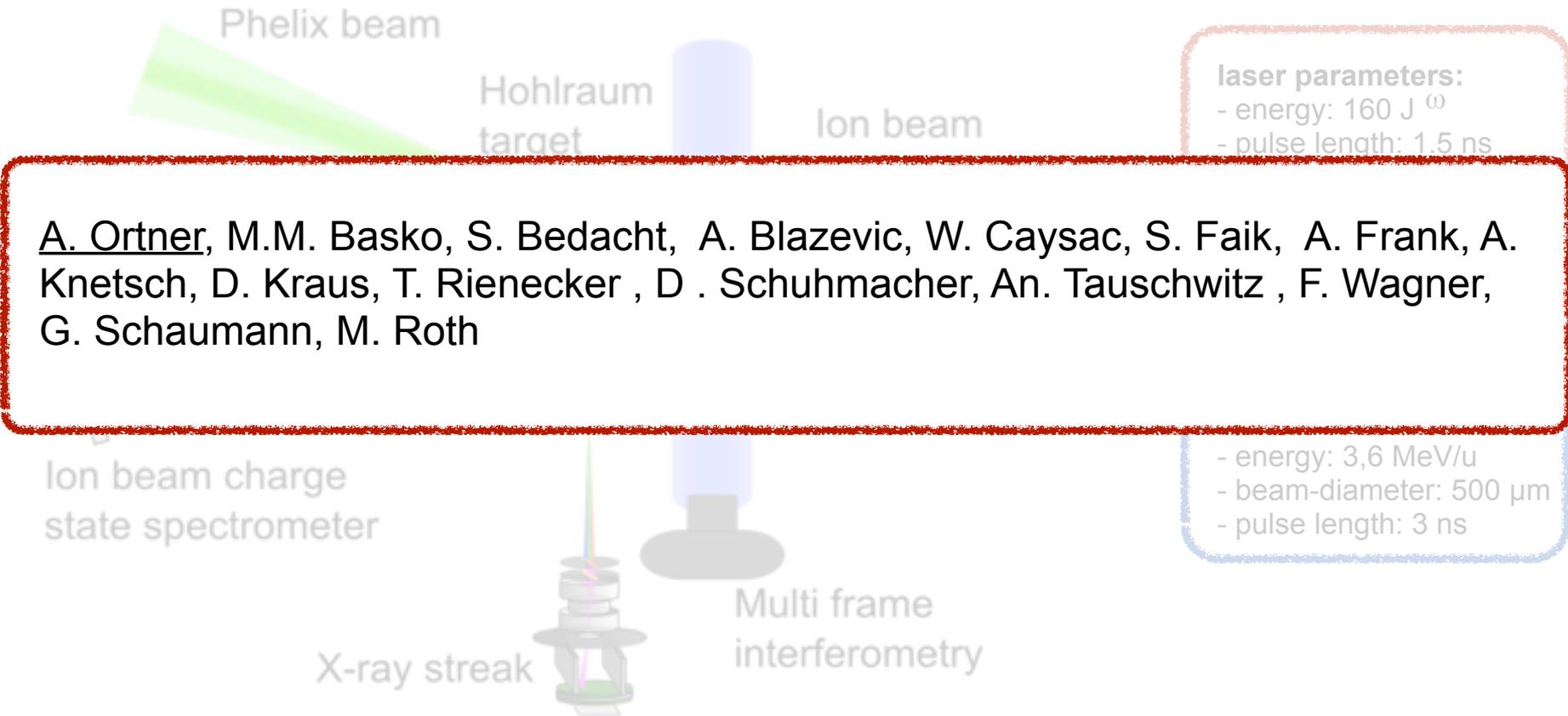
solide theorien
viele Daten
gut vermessen



from D.Gericke et al. (1999 & 2003)

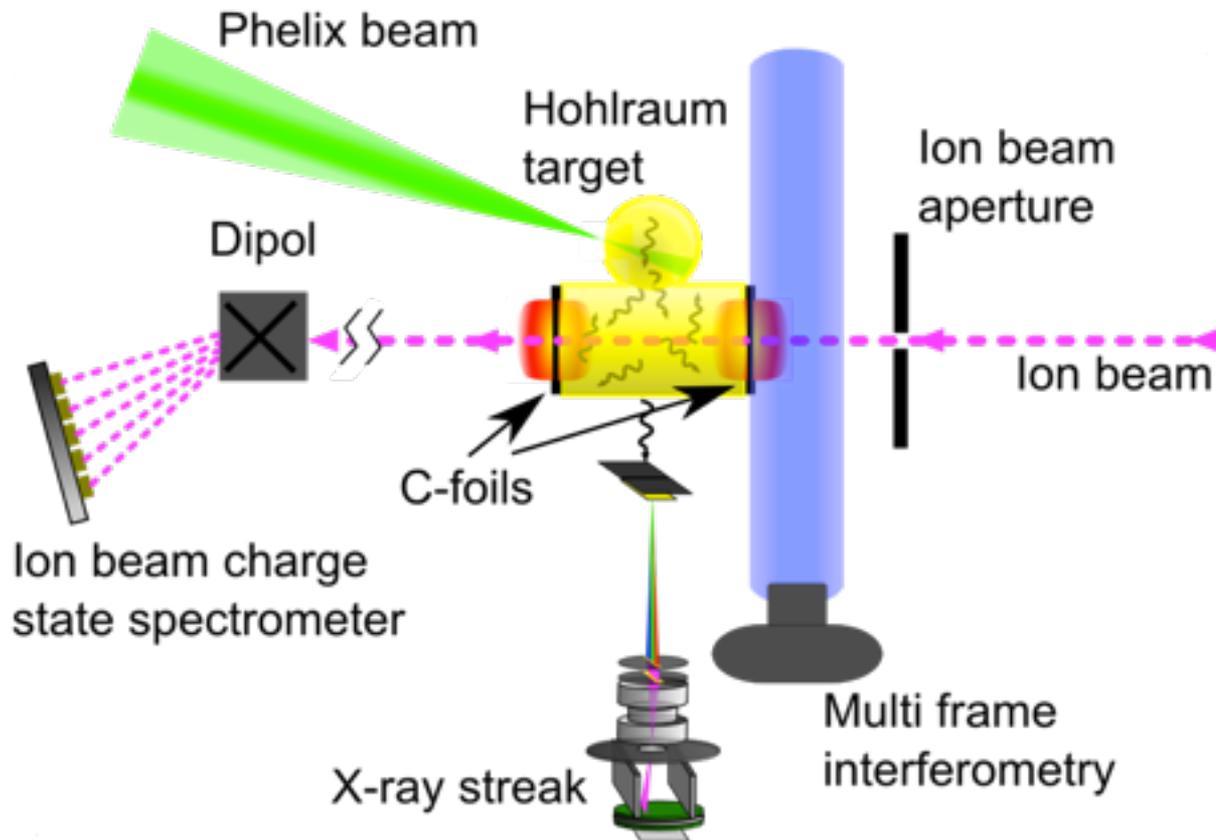
indirect heating with hohlraum generated x-ray

A. Ortner, M.M. Basko, S. Bedacht, A. Blazevic, S. Faik, A. Frank, A. Knetsch, D. Kraus, T. Rienecker, D. Schuhmacher, An. Tauschwitz, F. Wagner, G. Schaumann, M. Roth



indirect heating with hohlraum generated x-ray

A. Ortner, M.M. Basko, S. Bedacht, A. Blazevic, S. Faik, A. Frank, A. Knetsch, D. Kraus, T. Rienecker, D. Schuhmacher, An. Tauschwitz, F. Wagner, G. Schaumann, M. Roth



laser parameters:

- energy: 160 J ω
- pulse length: 1.5 ns
- $\lambda = 532 \text{ nm}$ (2 λ)

heavy-ion beam:

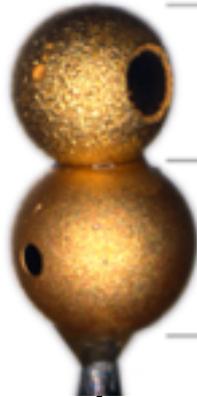
- Calcium 17+
- energy: 3,6 MeV/u
- beam-diameter: 500 μm
- pulse length: 3 ns

development of hohlraumtargets

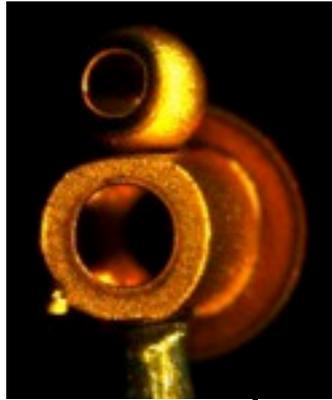
fabrication in the target laboratory of TUD (Dr. Gabriel Schaumann)



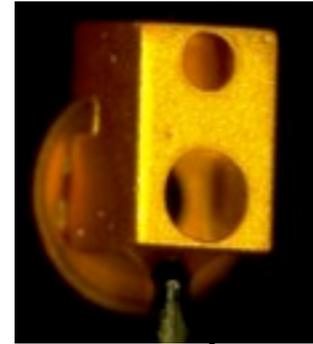
2006



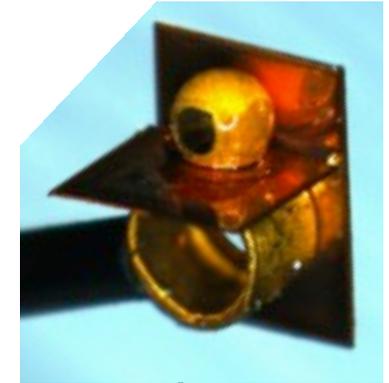
2008



2010



2011



2012

evolution of the target geometry

dimensions:

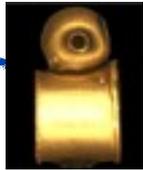
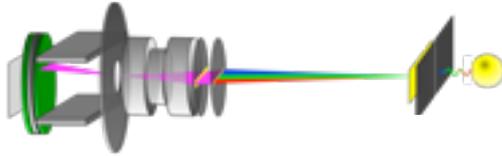
- upper hohlraum (sphere): $600\mu\text{m}$
- lower hohlraum (cylinder): $800 - 1000\mu\text{m}$, $l = 625 - 750\mu\text{m}$
- laser entrance hole: $300\mu\text{m}$
- $15\mu\text{m}$ gold

production techniques:

- electroplating
- laser beam cutting
- micro chipping

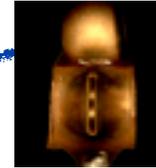
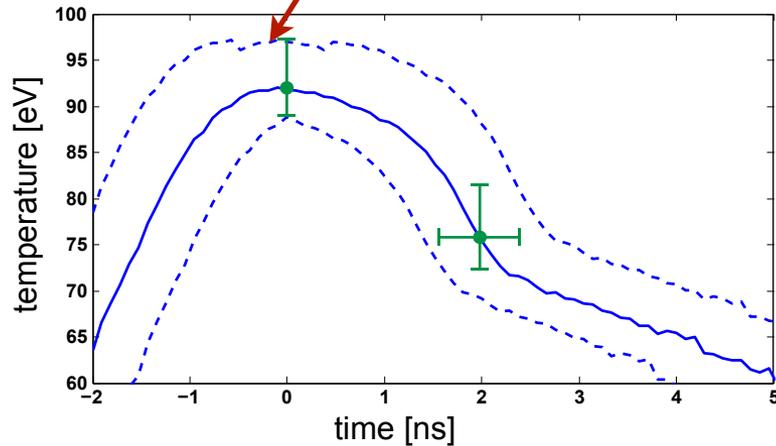
radiation temperature of the hohlraums

x-ray streak camera



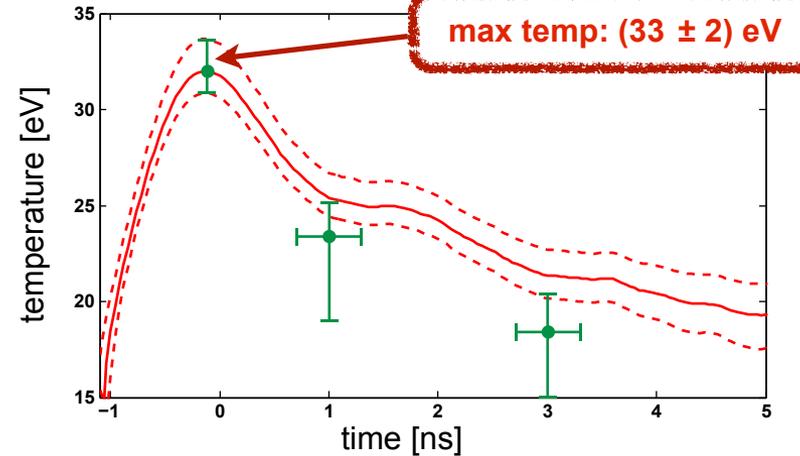
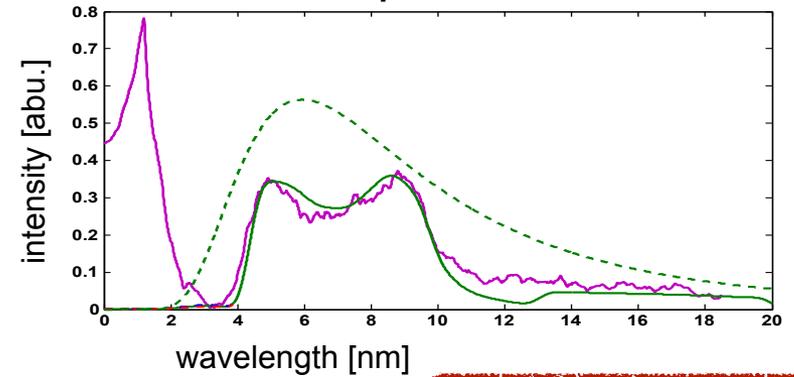
temperature in primary hohlraum

max temp: (92 ± 4) eV



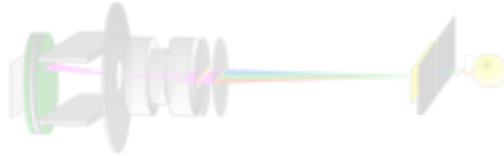
temperature in secondary hohlraum

spectra

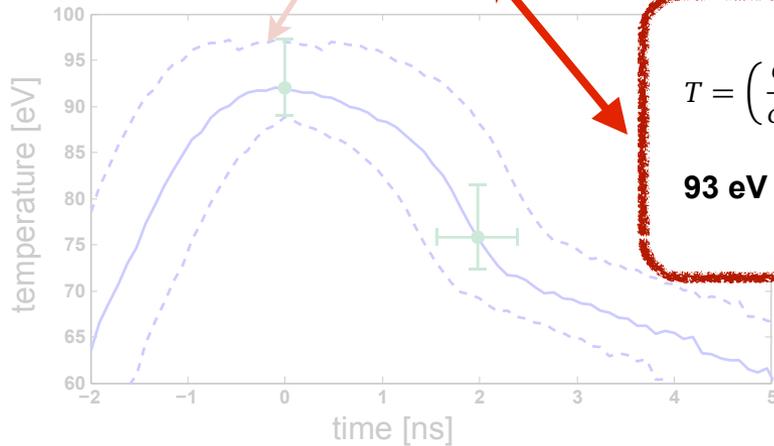


radiation temperature the hohlraums

x-ray streak camera



temperature in primary hohlraum



max temp: (92 ± 4) eV

theory

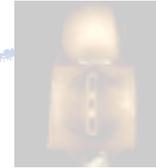
$$T = \left(\frac{c}{\sigma}\right)^{1/4} t^{\alpha/4} (S_s - f\sigma T^4)^{\beta/4}$$

93 eV ✓

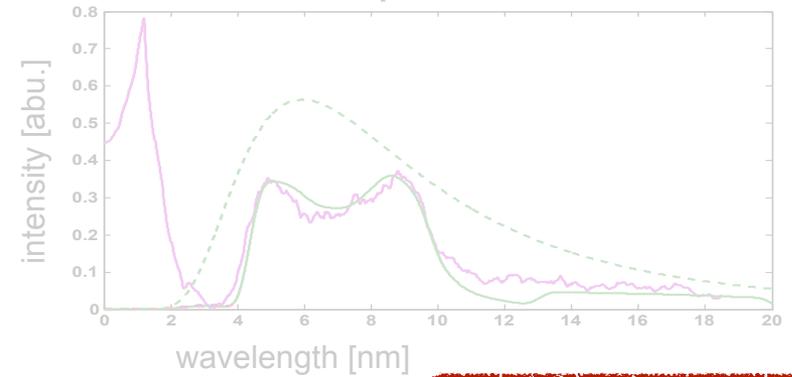
35 eV ✓

G.D. Tsakiris, 1987 & 1992

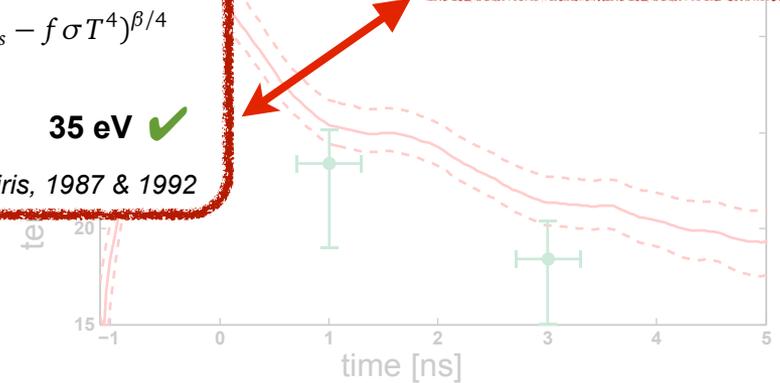
temperature in secondary hohlraum



spectra



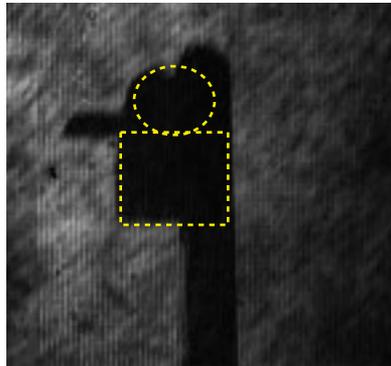
max temp: (33 ± 2) eV



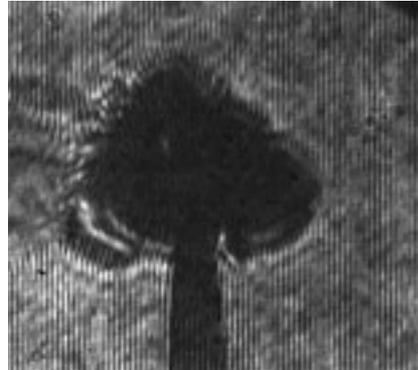
electron density of x-ray heated carbon

multiframe interferometry

reference



no shielding



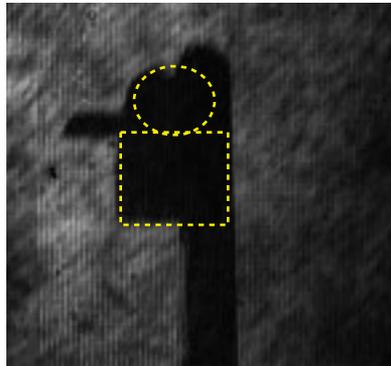
shielding



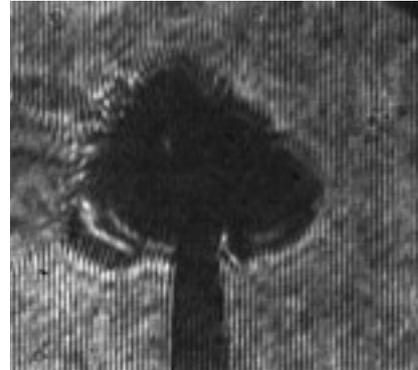
electron density of x-ray heated carbon

multiframe interferometry

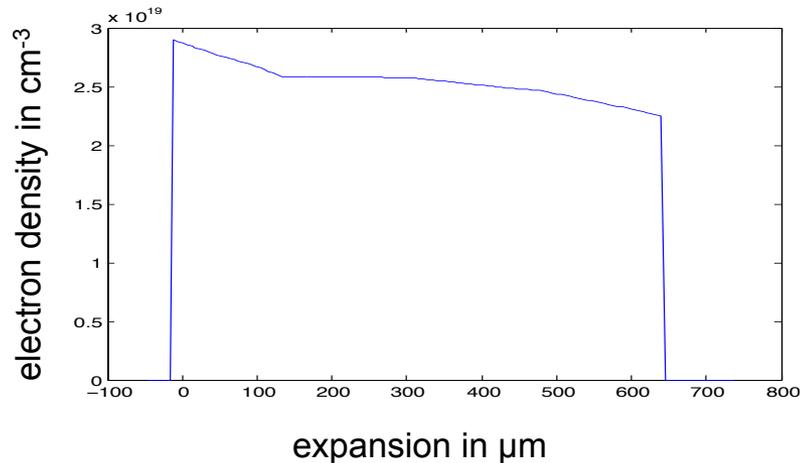
reference



no shielding



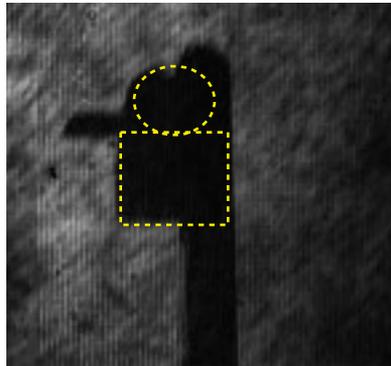
shielding



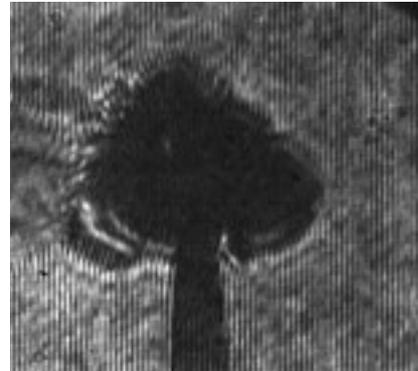
electron density of x-ray heated carbon

multiframe interferometry

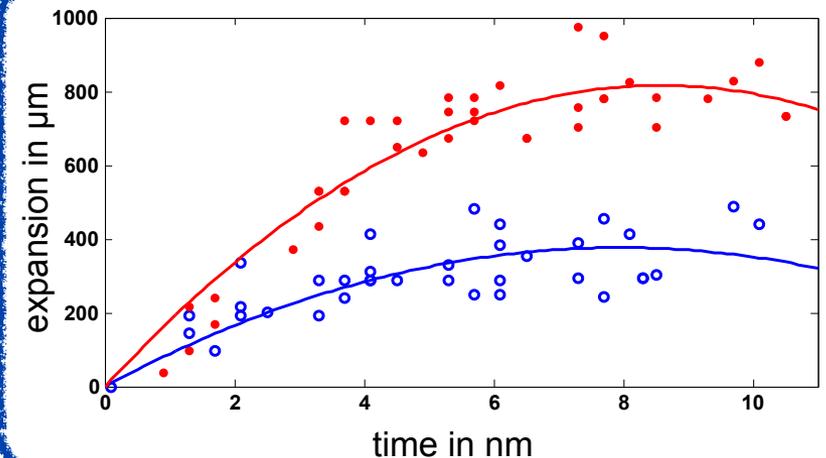
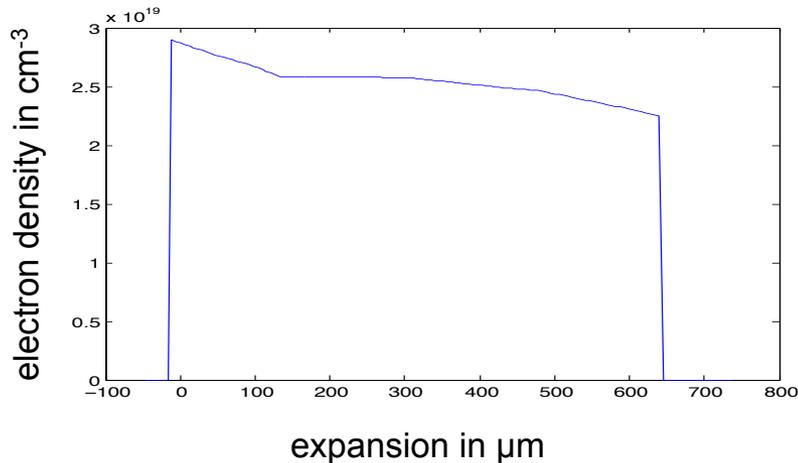
reference



no shielding



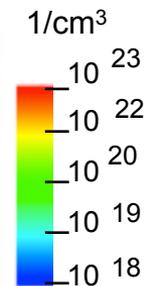
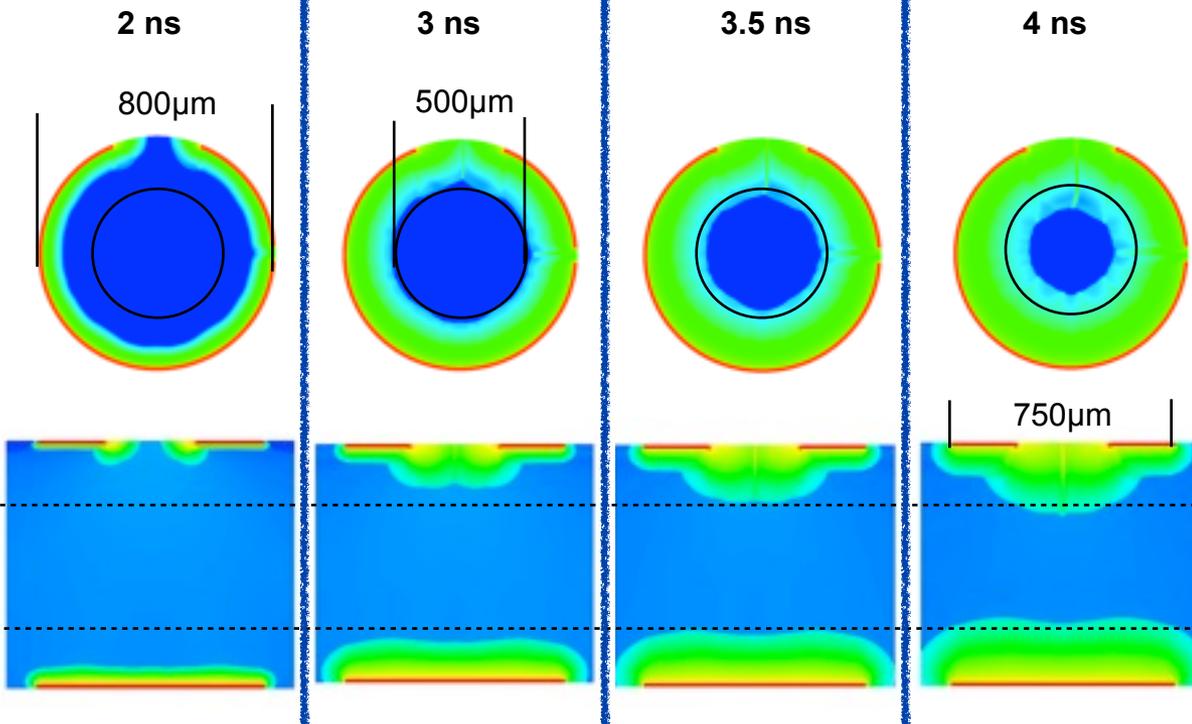
shielding



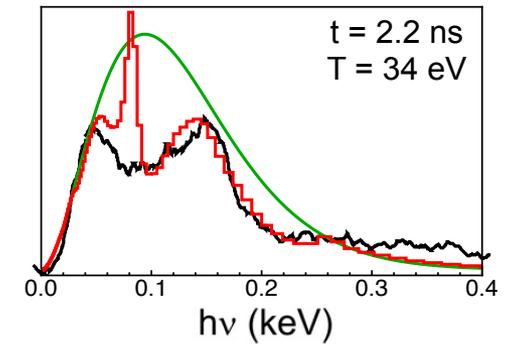
RALEF 2D simulations

simulations by S. Faik, M. Basko, An. Tauschwitz

electron density of Au



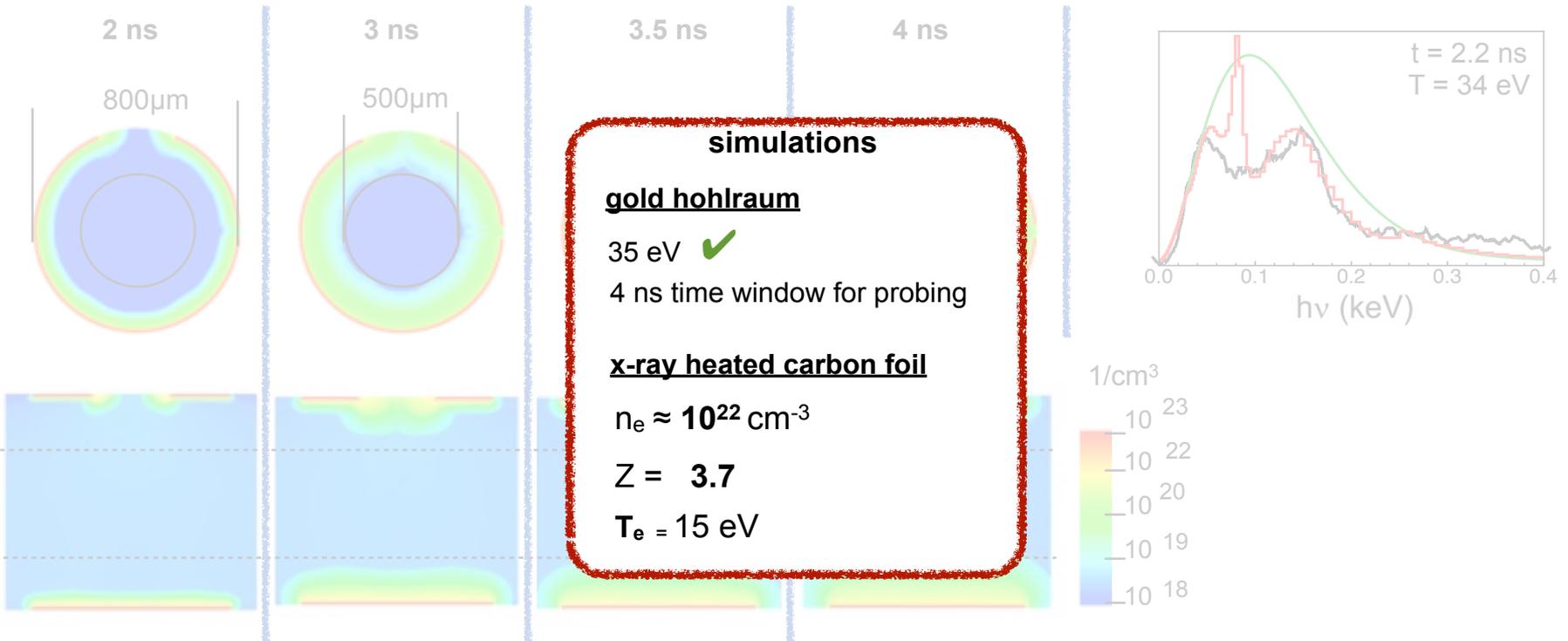
hohlraum spectra



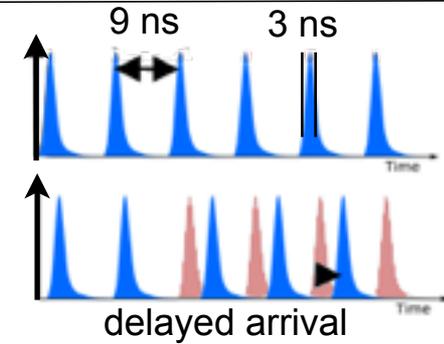
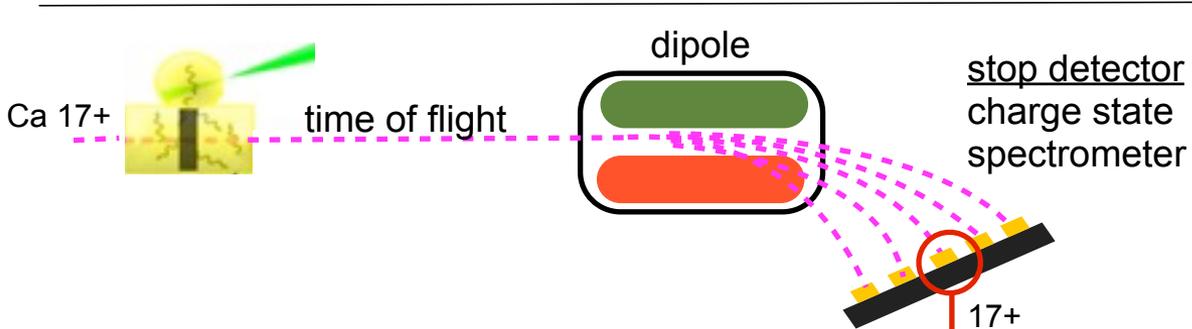
RALEF 2D simulations

simulations by S. Faik, M. Basko, An. Tauschwitz

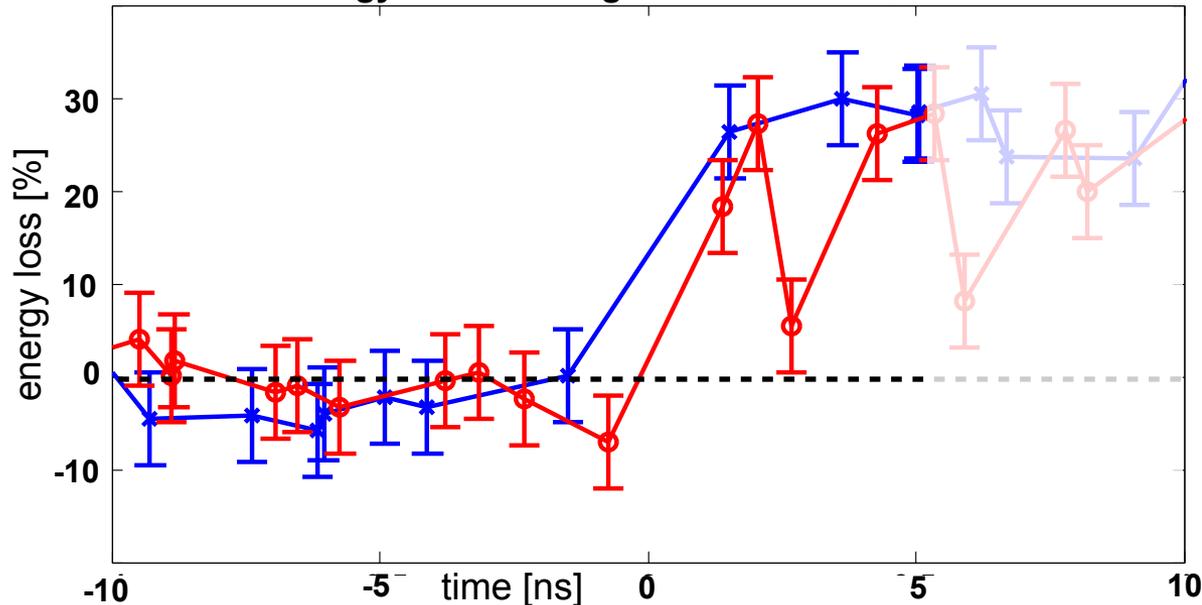
electron density of Au



energy loss measurements



energy loss of charge state Ca 17+



+ 30% energy loss

theoretical calculations
with CASP and ETACHA in
progress

direct laser heating probed with slow ions

W. Cayzac, V. Bagnoud, A. Blazevic, A. Frank, D. Gericke, P.L. Grande, A. Knetsch, L. Hallo, G. Malka, P. Neumayer, A. Ortner, T. Schlegel, F. Wagner, G. Schaumann, M. Roth

Pinhole
500 μm

Nhelix

Phelix

laser parameters:

- PHELIX: 30 l, 7 ns, 527 nm

W. Cayzac, V. Bagnoud, A. Blazevic, A. Frank, D. Gericke, P.L. Grande, A. Knetsch, L. Hallo, G. Malka, P. Neumayer, A. Ortner, T. Schlegel, F. Wagner, G. Schaumann, M. Roth

interferometry

experimental details:

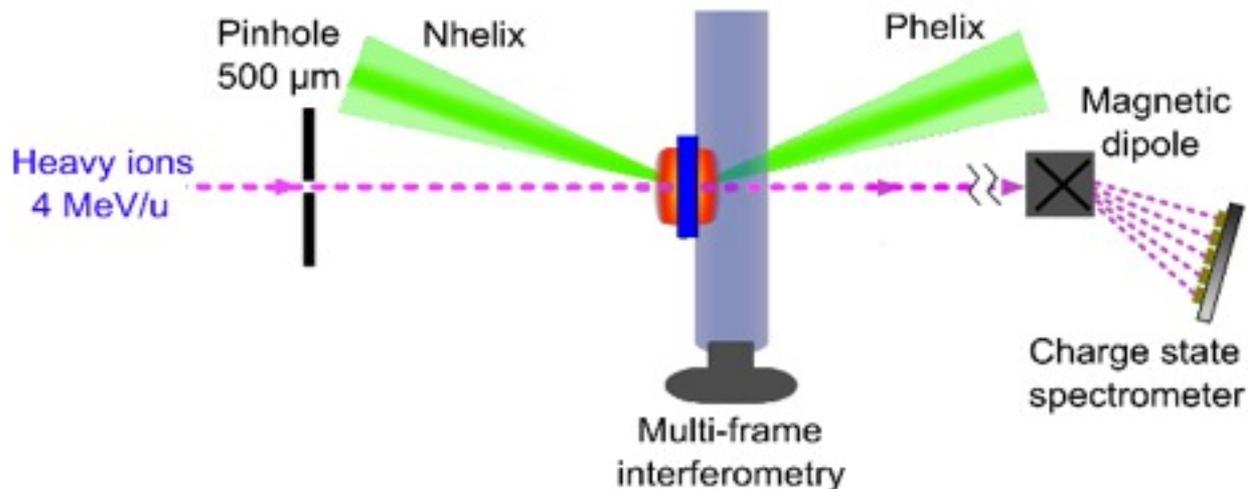
- slowdown of ions with solid carbon foil
- $E_{\text{ion}} \sim 0.3\text{--}1 \text{ MeV/u}$, $v_{\text{ion}}/v_{\text{th}} \sim 1\text{--}2$

expected energy and angle straggling at 500keV/u: 10% with 3.5°

energy: 4–8 meV/u
light ions: C, O, Ne
500 μm beam diameter

achieved results in direct laser heating: direct laser heating probed with swift ions

A. Frank, M.M. Basko, V. Bagnoud, A. Blazevic, W. Cayzac, D. Gericke, P.L. Grande, P. Neumayer, T. Schlegel, An. Tauschwitz, G. Schaumann, M. Roth



laser parameters:

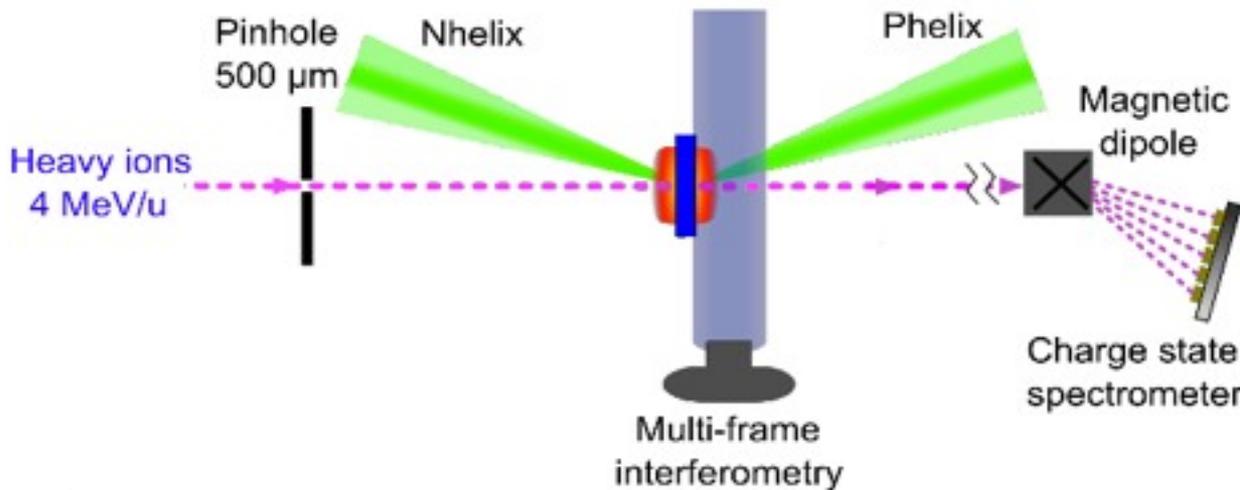
- PHELIX: 30 J, 7 ns, 527 nm
- NHELIX: 30 J, 7 ns, 532 nm

heavy-ion beam:

- energy: 4–6 MeV/u
- ions: Ar
- 500 μm beam diameter

achieved results in direct laser heating: direct laser heating probed with swift ions

A. Frank, M.M. Basko, V. Bagnoud, A. Blazevic, W. Cayzac, D. Gericke, P.L. Grande, P. Neumayer, T. Schlegel, An. Tauschwitz, G. Schaumann, M. Roth



laser parameters:

- PHELIX: 30 J, 7 ns, 527 nm
- NHELIX: 30 J, 7 ns, 532 nm

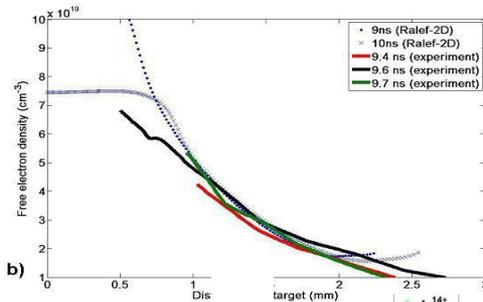
heavy-ion beam:

- energy: 4–6 MeV/u
- ions: Ar
- 500μm beam diameter

plasma parameters :

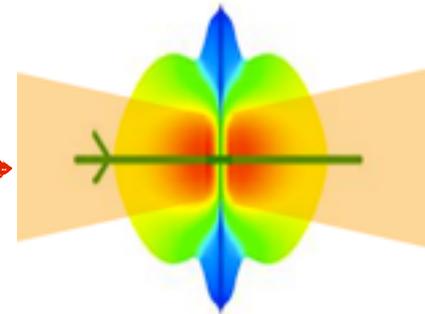
experimental
result:

$$- n_e \approx 10^{19} \text{ cm}^{-3}$$



benchmark
hydrodynamic

simulations
(RALEF 2D)



simulation
results:

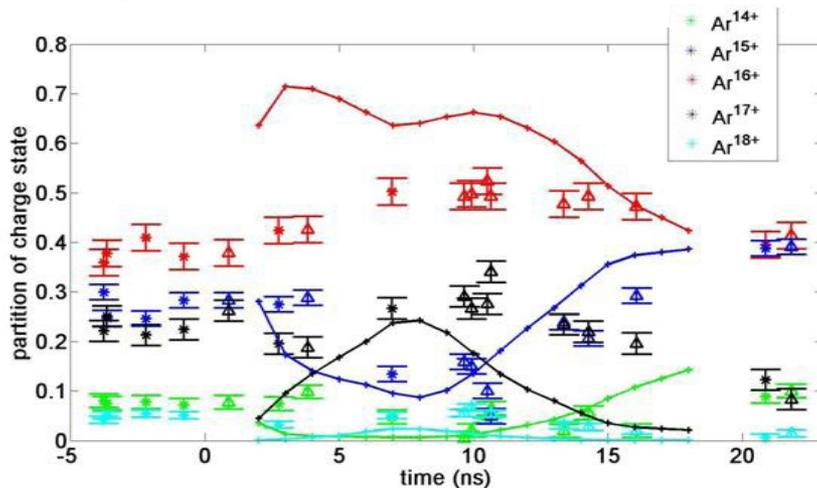
- $T_e \approx 200 \text{ eV}$
- fully ionized
- strong gradients

achieved results in direct laser heating: energy loss and charge transfer in ideal plasma

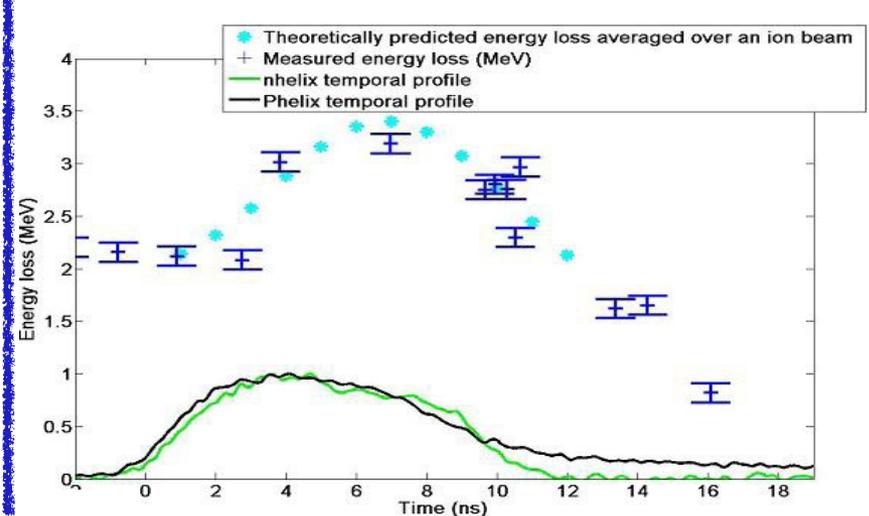
Monte Carlo simulation for the charge state evolution in the plasma

Calculation of charge state dependent stopping power

charge state evolution

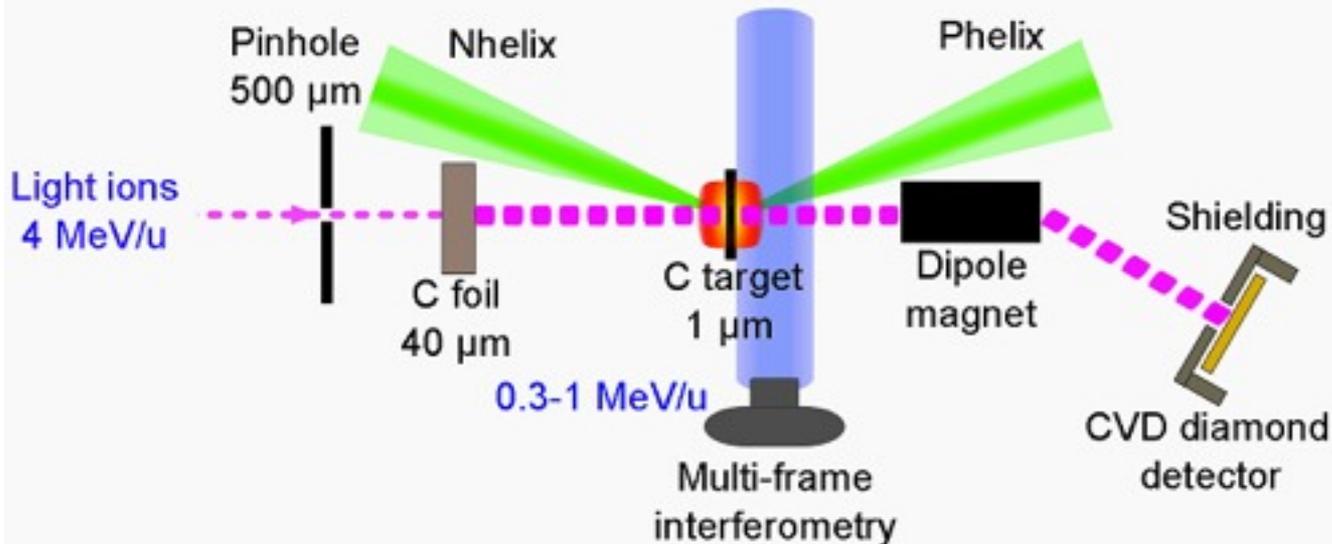


energy loss of Ar in carbon plasma



direct laser heating probed with slow ions

W. Cayzac, V. Bagnoud, A. Blazevic, A. Frank, D. Gericke, P.L. Grande, A. Knetsch, L. Hallo, G. Malka, P. Neumayer, A. Ortner, T. Schlegel, F. Wagner, G. Schaumann, M. Roth



laser parameters:

- PHELIX: 30 J, 7 ns, 527 nm
- NHELIX: 30 J, 7 ns, 532 nm

heavy-ion beam:

- energy: 4–6 MeV/u
- light ions: C, O, Ne
- 500 μm beam diameter

experimental details:

- slow down of ions with solid carbon foil
- $E_{\text{ion}} \sim 0.3\text{--}1 \text{ MeV/u}$, $v_{\text{ion}}/v_{\text{th}} \sim 1\text{--}2$

expected energy and angle straggling at 500keV/u: 10% with 3.5°

laser ion generation, handling and transport

S. Busold, A. Blazevic, C. Brabetz, H. Al-Omari, T. Burris-Mog, M. Joost, F. Kroll, D. Schumacher, B. Zielbauer, V. Bagnoud, I. Hofmann, T. Cowan, M. Roth



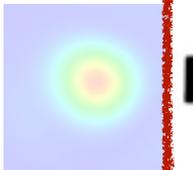
S. Busold, A. Blazevic, C. Brabetz, H. Al-Omari, T. Burris-Mog, M. Joost, F. Kroll, D. Schumacher, B. Zielbauer, V. Bagnoud, I. Hofmann, T. Cowan, M. Roth

collaboration of five institutes

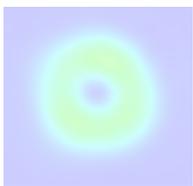


focus shape

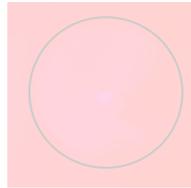
flat top focus



dounut focus



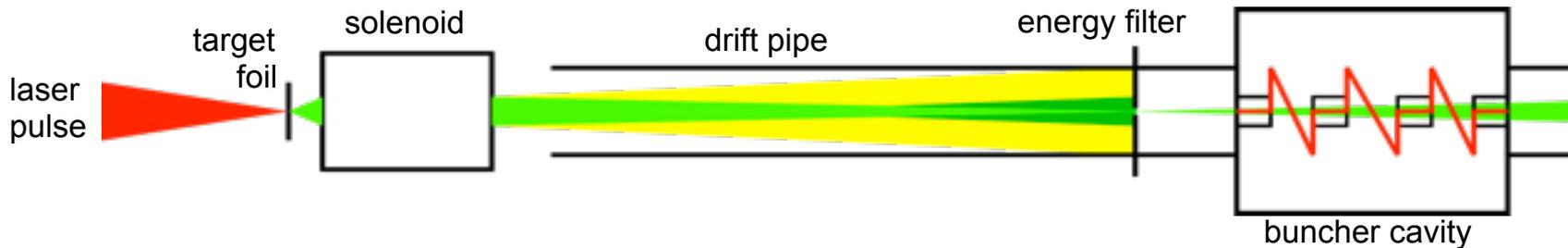
10^{10} particle



10^5 particle

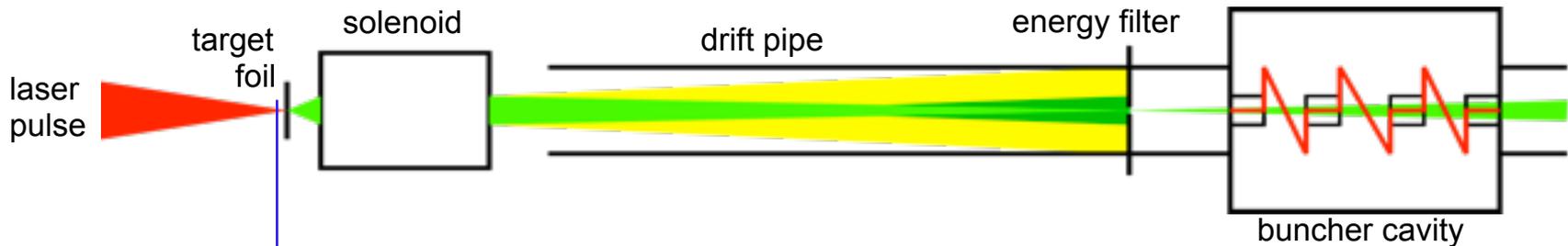
laser ion generation, handling and transport

S. Busold, A. Blazevic, C. Brabetz, H. Al-Omari, T. Burris-Mog, M. Joost, F. Kroll, D. Schumacher, B. Zielbauer, V. Bagnoud, I. Hofmann, T. Cowan, M. Roth



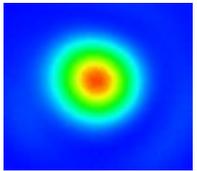
laser ion generation, handling and transport

S. Busold, A. Blazevic, C. Brabetz, H. Al-Omari, T. Burris-Mog, M. Joost, F. Kroll, D. Schumacher, B. Zielbauer, V. Bagnoud, I. Hofmann, T. Cowan, M. Roth

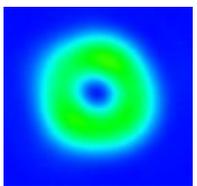


focus shaping

flat top focus

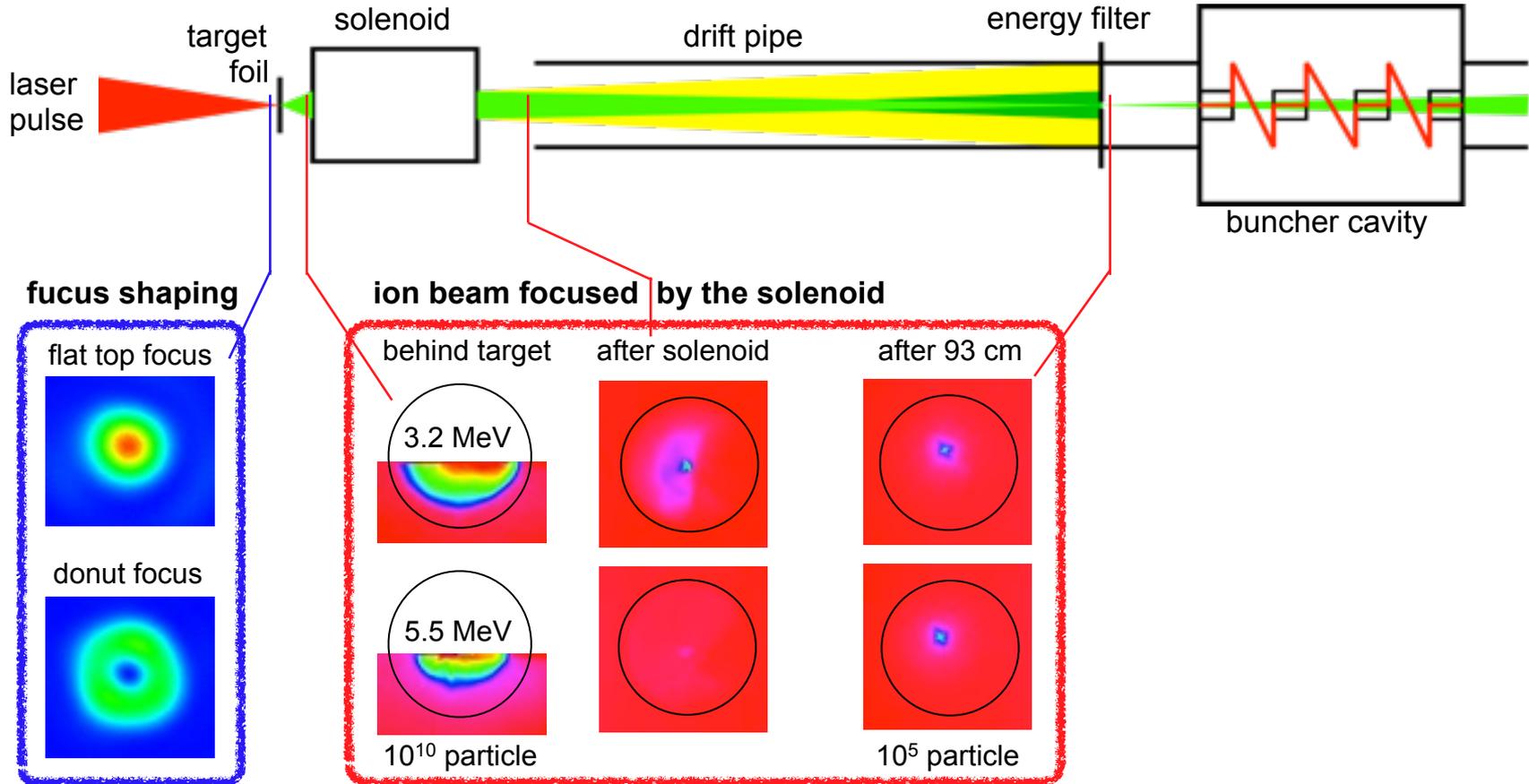


donut focus



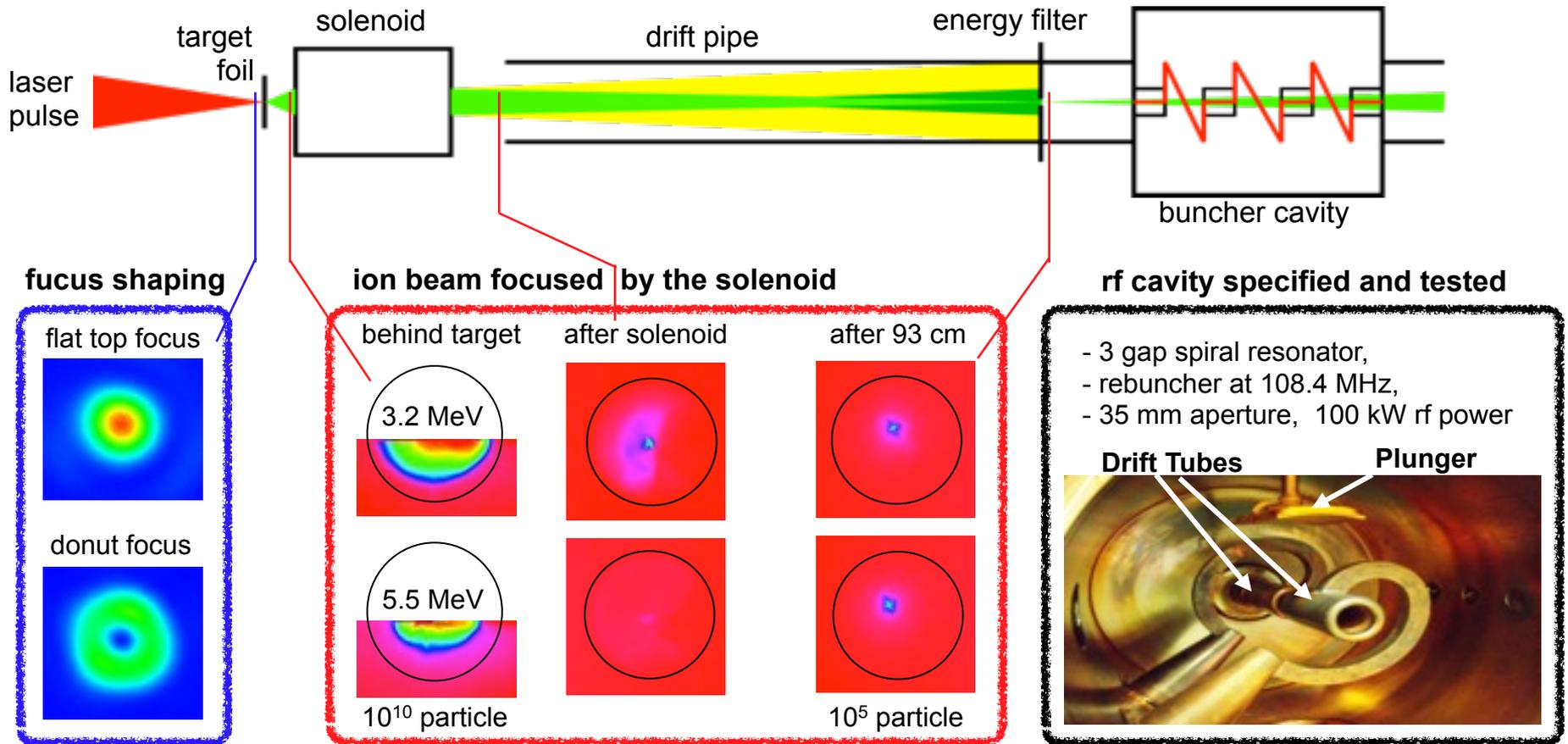
laser ion generation, handling and transport

S. Busold, A. Blazevic, C. Brabetz, H. Al-Omari, T. Burris-Mog, M. Joost, F. Kroll, D. Schumacher, B. Zielbauer, V. Bagnoud, I. Hofmann, T. Cowan, M. Roth



laser ion generation, handling and transport

S. Busold, A. Blazevic, C. Brabetz, H. Al-Omari, T. Burris-Mog, M. Joost, F. Kroll, D. Schumacher, B. Zielbauer, V. Bagnoud, I. Hofmann, T. Cowan, M. Roth



finished :-) thank you!

S. Busold, A. Blazevic, C. Brabetz, H. Al-Omari, T. Burris-Mog, M. Joost, F. Kroll, D. Schumacher, B. Zielbauer, V. Bagnoud, I. Hofmann, T. Cowan, M. Roth



laser pulse target solenoid drift pipe energy filter

Thank you!



flat top
dounut focus
5.5 MeV
 10^{10} particle
 10^5 particle
Plunger

and tested
for,
MHz,
00 kW rf power

multiframe interferometry / shadowgraphy

